IN DEPTH

Protecting Cardiovascular Health From Wildfire Smoke

Michael B. Hadley, MD; Sarah B. Henderson, PhD; Michael Brauer, ScD; Rajesh Vedanthan, MD

ABSTRACT: Wildfire smoke is a rapidly growing threat to global cardiovascular health. We review the literature linking wildfire smoke exposures to cardiovascular effects. We find substantial evidence that short-term exposures are associated with key cardiovascular outcomes, including mortality, hospitalization, and acute coronary syndrome. Wildfire smoke exposures will continue to increase over the majority of Earth’s surface. For example, the United States alone has experienced a 5-fold increase in annual area burned since 1972, with 82 million individuals estimated to be exposed to wildfire smoke by midcentury. The associated rise in excess morbidity and mortality constitutes a growing global public health crisis. Fortunately, the effect of wildfire smoke on cardiovascular health is modifiable at the individual and population levels through specific interventions. Health systems therefore have an opportunity to help safeguard patients from smoke exposures. We provide a roadmap of evidence-based interventions to reduce risk and protect cardiovascular health. Key interventions include preparing health systems for smoke events; identifying and educating vulnerable patients; reducing outdoor activities; creating cleaner air environments; using air filtration devices and personal respirators; and aggressive management of chronic diseases and traditional risk factors. Further research is needed to test the efficacy of interventions on reducing cardiovascular outcomes.

Key Words: air pollution cardiovascular diseases climate change global health smoke wildfires

Unplanned landscape fires, or wildfires, are a threat to global cardiovascular health. Wildfire smoke is a key contributor to global fine particulate matter (PM$_{2.5}$; particulate matter air pollution [PM] <2.5 µm in diameter) air pollution, which is the leading environmental risk factor for cardiovascular disease (CVD).$^1$ PM$_{2.5}$ is responsible for an estimated 13.3% of all cardiovascular deaths globally (2.5 million), mainly through ischemic heart disease and stroke.$^1$ The PM$_{2.5}$ from global landscape fire smoke alone is associated with more than 675,000 deaths annually worldwide,$^2$ mostly with cardiovascular causes.

The threat of wildfire smoke to cardiovascular health is growing.$^3$-$^6$ Since 2001, climate change, curtailing of prescribed burns, and the expanding wildland-urban interface have led to a 77% increase in the daily population exposure to wildfire smoke.$^6$ Notable recent fires have decimated wildlands across North America, Australia, and Brazil, with the United States experiencing a 5-fold increase in annual area burned since 1972.$^7$ Through midcentury, 82 million individuals living in the United States may be exposed to wildfire smoke.$^8$ Projections indicate that wildfires will increase in size, intensity, frequency, and duration over the majority of Earth’s land surface.$^3$ Regions with the greatest increase in wildfire potential include the Amazon basin, sub-Saharan Africa, Central and Southern Asia, Australia, Central America, and the United States$^{10}$ (Figure 1). Smoke from these wildfires may be transported at hazardous concentrations for thousands of kilometers.$^3$ The associated rise in excess morbidity and mortality constitutes a growing public health crisis.

The effect of wildfire smoke on cardiovascular health is modifiable at the individual and population levels through specific interventions. Health systems therefore have an opportunity and a responsibility to help protect their patients from the harmful effects of wildfire smoke. In this article, we discuss the mechanisms by which wildfire smoke affects cardiovascular health and specific interventions clinicians and health systems can take to protect their patients. Our

The opinions expressed in this article are not necessarily those of the editors or of the American Heart Association.

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conclusions generally apply to other types of landscape fires, including land clearing fires and agricultural burning, which pose similar risks to cardiovascular health.

HEALTH EFFECTS OF WILDFIRES

Wildfires can affect cardiovascular health through several pathways (Figure 2). We focus primarily on the cardiovascular effects of smoke exposures, which are responsible for the greatest burden of attributable disease. Recent systematic reviews by Chen et al.11 and Reid et al.12 summarize the primary literature linking wildfire smoke exposure to subclinical cardiovascular effects. In addition, a growing literature links wildfire smoke to more severe outcomes such as cardiovascular mortality.13 A wealth of studies also demonstrate cardiovascular outcomes associated with exposures to PM2.5, the dominant pollutant in wildfire smoke.14-16

The totality of evidence is sufficient to draw associations between wildfire smoke exposures and cardiovascular outcomes.11,12,17

Toxic Components of Wildfire Smoke

Wildfire smoke arises principally from incomplete combustion of cellulose, lignin, resins, waxes, sugars, and inorganic salts found in wood.16 The result is a heterogeneous mixture of gaseous and particulate components, including particulate matter and a range of gaseous and semivolatile pollutants.17,18 In addition, volatile organic compounds and NOx react with sunlight to create the secondary pollutant ozone (O3).17,18 The exact composition and toxicity of emitted pollutants vary by type and moisture content of fuel, type, and temperature of fire (eg, flaming versus smoldering), landscape characteristics, rate of fuel consumption, and meteorological conditions.5,11,17,19 If wildfires move into communities, additional chemicals from plastics and other anthropogenic materials will be released into the air.20

Of these toxic components, PM2.5 has the largest body of evidence implicating adverse cardiovascular effects.14-16 In 2010, the American Heart Association released a statement that reviewed hundreds of studies and concluded that the overall evidence is consistent with a causal relationship between PM2.5 exposure and cardiovascular morbidity and mortality.15 Recently, another American Heart Association statement concluded that PM from wildfires is associated with increased
cardiovascular events with effect estimates comparable with those of ambient PM$_{2.5}$ from other sources. PM$_{2.5}$ also serves as the best metric for smoke exposure during wildfire events because it is routinely measured, consistently elevated, and predictive of public health threats. However, PM$_{2.5}$ serves as a proxy for the more complex wildfire smoke mixture; the potential role of other copollutants may also be relevant to health effects.

**Timescales of Exposure**

Most studies of wildfire smoke have examined the acute health effects of short-term exposures (hours to days). Findings are consistent with the broader literature on short-term exposures to PM$_{2.5}$ from other sources. Few studies have investigated the long-term health effects of repeated wildfire smoke exposures. Given the episodic nature of wildfires, it is problematic to extrapolate from studies of chronic urban PM$_{2.5}$ to wildfire smoke. Further studies on repeated wildfire exposures are urgently needed to estimate the cardiovascular effects.

**Pathophysiology of Wildfire Smoke Exposure**

Inhaled PM triggers initiating pathways that lead to the development of cardiovascular risk factors and outcomes (Figure 2). The biochemical pathways by which PM exposures lead to cardiovascular outcomes have been

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**Figure 2. Pathophysiology of cardiovascular disease attributed to wildfires.**

Environmental factors including climate change, forest management practices, and the growth of the wildland-urban interface have led to increased incidence and severity of wildfires. Smoke from wildfires contains hazardous pollutants that can trigger a cascade of cardiovascular effects resulting in adverse outcomes. These effects have been well-defined for short-term exposures, with further research needed for long-term or repeated exposures. Adverse outcomes may be amplified by pulmonary disease, mental health effects, and high temperatures. ED indicates emergency department; PAH, polycyclic aromatic hydrocarbon; PM, particulate matter air pollution; and PM2.5, fine particulate matter.
reviewed extensively elsewhere. Here we review recent studies investigating the health effects of wildfire smoke specifically.

**Initiating Pathways**

Studies and reviews of ambient PM pollution have elucidated numerous harmful *initiating pathways*. Inhaled PM deposits in the alveoli, damages local structures, and leads to a cascade of oxidative stress, activation of inflammatory cells, impaired microvascular function, platelet activation, hypercoagulability, and decreased heart rate variability. These effects may be modified by host susceptibility (eg, individuals with pro-inflammatory conditions) or the presence of copollutants (eg, ozone inactivates native antioxidant defenses).

Studies specifically of wildfire smoke and woodsmoke have observed similar effects. In humans, controlled clinical exposure studies with woodsmoke have demonstrated impaired microvascular function, elevated central arterial stiffness, decreased heart rate variability, elevated markers of oxidative stress and hypercoagulability (eg, fibrinogen, IL-1β, and TNF-α), and cell cycle disruption and cytotoxicity. In vivo animal studies show that wildfire-derived PM exposure is associated with higher oxidative stress, inflammatory cell lines, cytokine release, and antioxidant depletion. In vitro studies also have shown that exposure to wildfire- or woodsmoke-derived PM is associated with higher inflammatory responses, reactive oxygen species, cell death, DNA fragmentation, and reduced antioxidant levels.

**Development of Cardiovascular Risk Factors**

**Elevated Blood Pressure**

The initiating pathways of impaired vasodilation, elevated arterial stiffness, endothelial dysfunction, and autonomic dysfunction all lead to elevations in blood pressure. Controlled-exposure studies consistently demonstrate a linear relationship between ambient PM exposure and blood pressure elevations. The existing literature on PM exposure provides a consistent picture. Ambient exposures to PM from forest and peat fires have been associated with short-term elevations in blood pressure. Similarly, controlled clinical exposure studies with woodsmoke in humans have demonstrated associations with higher blood pressure.

**Atherosclerosis**

Ambient air pollution has been associated with coronary and carotid atherosclerosis. Proposed mechanisms include vascular inflammation, macrophage infiltration, and accumulation of oxidized lipids. In addition, PM exposure has been associated with the development of more vulnerable atherosclerotic plaques. Early studies on woodsmoke exposure are consistent with these findings. Cohort studies of burning biomass fuel indoors have shown association with higher carotid intima media thickness and prevalence of carotid plaques. In addition, murine and in vitro studies have found that gaseous components of woodsmoke (eg, SO₂, NH₃, NOₓ, and CO) are important in this proatherosclerotic response.

Destabilization of vulnerable atherosclerotic plaques is a key mechanism by which short-term exposures to wildfire smoke may lead to acute cardiovascular events, including stroke or acute coronary syndrome. This may occur in individuals with known atherosclerotic disease or reveal previously subclinical atherosclerosis. Because these acute effects require an underlying vulnerability, individuals without atherosclerotic plaques are unlikely to experience such outcomes from short-term smoke exposures.

**Other Effects**

Ambient air pollution exposures have been associated with the development of dyslipidemia, insulin resistance, diabetes, gestational diabetes, and obesity, which are major risk factors for atherosclerotic CVD. In addition, these exposures have been associated with left ventricular hypertrophy, diastolic dysfunction, and myocardial fibrosis, which are risk factors for heart failure. These effects are associated more strongly with chronic ambient air pollution exposures and have not been studied specifically in human populations exposed to wildfire smoke.

**Modifying Effects**

Several additional mechanisms modify the relationship between wildfire smoke exposures and cardiovascular outcomes (Figure 2).

**Heat Effects**

Wildfires often coincide with warm weather. Elevated ambient temperatures are associated with higher rates of cardiovascular outcomes. A recent study of 652 cities found that the association between PM and cardiovascular mortality was stronger in areas with higher annual mean temperatures. Similarly, a 1°C increase in temperature has been associated with a 3.4% rise in cardiovascular mortality. Smoke exposures interact with high temperatures to worsen cardiovascular outcomes. For example, a study of a wildfire event near Moscow found that interactions between high temperatures and air pollution from wildfires contributed to cardiovascular deaths in excess of an additive effect.

**Mental Illness**

Exposure to PM is associated with anxiety and depression after controlling for socioeconomic factors. In addition, qualitative studies have documented the disruptive effects of wildfires, including evacuations, school relocations, business closures, property loss, reduced outdoor and physical activity, food insecurity, and stress and uncertainty. Individuals thus affected are at higher risk for mental illness, including posttraumatic stress disorder, anxiety, depression, and insomnia.
This mental illness may persist for years after wildfire exposures, particularly among children and adolescents. Depression and anxiety are known predictors of accelerated atherosclerotic CVD.

**Pulmonary Disease**
Pulmonary disease exacerbations may precipitate cardiovascular outcomes by decreasing blood oxygenation or increasing right ventricular afterload. Epidemiological studies demonstrate that wildfire smoke exposure is associated with both acute and chronic respiratory illness, including pneumonia, lung cancer, asthma exacerbation, chronic obstructive pulmonary disease exacerbation, impaired gas exchange, and higher respiratory hospital admissions. In addition, wildfire smoke appears to be associated with higher risk of death from COVID-19.

**Community Disruptions**
Like other natural disasters, wildfires disrupt communities in ways that may have important consequences on cardiovascular health. For example, individuals may experience displacement from home, disrupted diet and exercise, interruption of social networks, and limited access to health care. A full review of these disruptions is beyond the scope of this article. Further research into these issues is warranted, especially to compare wildfires with other emergency and humanitarian situations such as hurricanes, earthquakes, military actions, and pandemic surges.

**Cardiovascular Outcomes**
The American Heart Association and European Society of Cardiology recognize PM$_{2.5}$ as a modifiable risk factor for cardiovascular outcomes. Key cardiovascular outcomes attributed to PM$_{2.5}$ include cardiovascular mortality, acute coronary syndrome, stroke, heart failure, and arrhythmias. A recent American Heart Association Scientific Statement estimated that the risk of these outcomes increases by 1% to 2% for short-term exposures and 5% to 10% for long-term exposures per 10 µg/m$^3$ of PM$_{2.5}$. Cardiovascular outcomes have been observed for both low-concentration and high-concentration exposures. Moreover, observational studies have found that lower ambient PM$_{2.5}$ exposures are associated with reductions in cardiovascular risk.

PM$_{2.5}$ is the pollutant most consistently elevated in wildfire smoke. A growing literature supports the claim that PM$_{2.5}$ from wildfires is at least as hazardous to cardiovascular health as PM$_{2.5}$ from other sources. A clear majority of studies demonstrate an association, although challenges inherent in studies of wildfire exposures may have led some epidemiologic studies to report null associations (see Future Directions). Current expert opinion is that the existing body of evidence on wildfire smoke supports an association with cardiovascular outcomes. Even if the risk of cardiovascular outcomes attributed to smoke exposures may be low for a single individual, widespread exposures that affect large populations result in a significant burden of disease. We summarize this literature below.

**Cardiovascular Mortality**
Numerous large prospective cohort studies have corroborated the relationship between ambient PM$_{2.5}$ and cardiovascular mortality. Looking specifically at wildfire smoke, a recent review identified 10 epidemiologic studies that have examined associations between cardiovascular mortality and short-term wildfire smoke exposures. Of these, 8 demonstrated significant positive associations, with varying magnitude of association. For example, a recent meta-analysis of data from 10 cities in Southern Europe demonstrated that 5-day cardiovascular mortality was higher by 6.3% (95% CI, 1.0 to 11.9) for days when PM <10 µm in diameter from forest fires exceeded 8 µg/m$^3$, compared with days when PM <10 µm in diameter from forest fires was <8 µg/m$^3$. The largest time series study on the effect of wildfire PM$_{2.5}$ exposures included 15 million cardiovascular deaths from 749 cities across 43 countries from 2000 to 2016. Using a random-effects meta-analysis, the authors found the relative risk of cardiovascular mortality was higher by 1.9% (95% CI, 1.3 to 2.5) per each 10 µg/m$^3$ increase in the 3-day moving of PM$_{2.5}$. Studies have also identified associations between wildfire smoke exposures and all-cause mortality.

**Cardiovascular Hospitalization**
Large epidemiologic studies have demonstrated that exposure to ambient air pollutants such as PM and NO$_x$ even at levels below current guidelines, are associated with higher risk of cardiovascular hospitalization. There are substantial data specifically on wildfire smoke exposures, with most studies showing an association between smoke exposures and emergency department visits for cardiovascular complaints, outpatient cardiovascular visits, hospital cardiovascular admissions, and intensive care unit admissions. The association appears particularly robust for elderly individuals. For example, a large study of hospitalizations in 692 US counties within 200 km of 123 wildfires found significantly higher cardiovascular hospitalizations associated with elevated PM$_{2.5}$ exposure, regardless of whether the PM$_{2.5}$ came from wildfires or another source. A recent time-series analysis of 148 million hospital admissions across Brazil from 2000 to 2015 found that cardiovascular hospital admissions in the day after exposure were higher by 1.1% (95% CI, 0.8 to 1.4) per 10 µg/m$^3$ increase in wildfire-related PM$_{2.5}$. A separate meta-analysis found that smoky days were associated with a 5.5% elevated risk of hospitalization for ischemic heart disease, although the CI crossed the null (95% CI, 0.8 to 10.1). Severe wildfire events may result in hospi-
tals exceeding capacity: a recent study projected that a simulated severe 7-day wildfire smoke event (120 µg/m³) would raise local intensive care unit admissions by 131%.39

**Cardiac Arrest**

Some case-crossover studies have identified associations between out-of-hospital cardiac arrest and exposure to ambient PM and ozone pollution.51,52 Air pollution exposures also have been associated with ventricular tachyarrhythmias, particularly in individuals with previous myocardial infarction and left ventricular dysfunction.53 Looking specifically at wildfire smoke exposures, out-of-hospital cardiac arrest has been associated with heavy smoke during the California wildfires of 2015 to 201754 as well as with elevated PM₂.₅ levels during the Australian wildfires of 2006 to 200755

**Acute Coronary Syndrome**

Many controlled studies have identified associations between air pollution exposure and incident fatal or nonfatal myocardial infarction, with the strongest associations seen for ST-segment–elevation myocardial infarction in individuals with pre-existing coronary artery disease.14,15,22 Looking specifically at wildfire smoke, exposure to PM₂.₅ from wildfires has been strongly associated with acute myocardial infarction in elderly individuals,56 as well as with emergency department visits46 and hospitalizations55 for acute myocardial infarction.

**Stroke**

Cohort studies, time series, and meta-analyses have found associations between air pollution exposures and stroke, both ischemic and hemorrhagic.21 Studies specific to wildfires have also demonstrated a significant association between smoke exposure and stroke46 or emergency department visits46 for cerebrovascular issues.46

**Heart Failure**

Air pollution exposures may accelerate ventricular remodeling and heart failure, resulting in a higher risk of heart failure hospitalization or death.57 In addition, a recent retrospective study of 21 800 patients with heart transplant suggests that exposure to PM₂.₅ is associated with higher mortality among this subpopulation.58 Looking specifically at woodsmoke, exposure to PM₂.₅ from wood-burning furnaces has been associated with a higher risk of hospitalization for heart failure in Australia.59

**PROTECTING PATIENTS AND COMMUNITIES**

Wildfire smoke threatens cardiovascular health, and reductions in PM₂.₅ exposures are associated with improved health outcomes.16 This presents an important public health opportunity to improve cardiovascular health by mitigating wildfire smoke exposures. In what follows, we discuss key actions for clinicians and their patients, as well as health systems and their communities (Figure 3).

**Risk Assessment**

Highly exposed individuals and susceptible individuals are 2 groups that are at higher risk of cardiovascular events (Figure 4). Highly exposed individuals are those exposed to high concentrations or durations of wildfire smoke. Susceptible individuals are those with a higher risk of a cardiovascular event for a given concentration of wildfire smoke exposure.

**Identifying High Exposure**

Smoke level forecasts are publicly available (Table). For example, the US Environmental Protection Agency (EPA) offers the Air Quality Index which provides real-time short-term PM₂.₅ exposure estimates with colored thresholds to clarify levels of risk.50 The AirNow wildfire page provides detailed information on air quality conditions affected by wildfires. Forecasts for future smoke conditions are also available.51,62

Disparities may exist for wildfire smoke exposures, with disproportionate exposures falling on Indigenous peoples, tribal populations, the elderly, and communities of low socioeconomic status.70,71 These groups also may have lower baseline health status and fewer resources to reduce their exposures or manage any health effects.20,70 Other highly exposed groups include individuals spending significant time outdoors, including children, athletes, agricultural workers, landscapers, construction crews, first responders, firefighters, etc.12,20

**Identifying Susceptibility**

Epidemiologic studies have identified groups with greater susceptibility to cardiovascular events attributed to wildfire smoke exposure, including individuals with pre-existing CVD; older adults (>65 years); women; Indigenous peoples; Black individuals; and low socioeconomic status individuals.11,17,20,46,55 By triggering cardiovascular events, smoke exposure may also unmask individuals with previously unknown CVD. The presence of multiple susceptible characteristics likely increases risk, although the exact interactions between risk factors require further investigation.

**Deciding Whether to Intervene**

Global and national organizations have produced guidelines for intervening at different thresholds of exposure. The World Health Organization recommends that average daily PM₂.₅ exposures not exceed 15 µg/m³ and average annual PM₂.₅ exposures not exceed 5 µg/m³.72 Currently, however, there is no evidence base to guide implementation of interventions at specific exposure cut-offs. Moreover, there appears to be no lower concentration of PM₂.₅ exposure that can be considered safe.18,22
as soon as there is smoke, there is risk for susceptible populations within the first hours of exposure. Therefore, the best approach is probably intervening to keep exposures As Low As is Reasonably Achievable (ALARA). During smoke events, all affected individuals—and particularly susceptible individuals—should have access to the following interventions to minimize exposures and associated cardiovascular events.

### Interventions to Protect Cardiovascular Health

We propose the following interventions to reduce smoke exposure, particularly for patients and communities at elevated risk of cardiovascular events. These interventions should be tailored to the individual or community and considered essential preparations for wildfire season (Figure 3). Implementation should account for personal factors that may encumber changes in patient behavior, including lack of capability, opportunity, or motivation.

#### Patient Education

Many individuals with CVD are unfamiliar with the harmful effects of air pollution or hold misconceptions (eg, “smoke is ‘natural’ so it can’t be harmful”). Such individuals are more likely to modify their behavior on the basis of messages they receive from clinicians.

Clinicians therefore have a responsibility to educate susceptible patients about the risks of smoke exposure, as well as specific interventions to mitigate harm. Clinicians in smoke-prone areas can direct patients to educational materials (Table).

#### Standard Primary and Secondary Prevention

Individuals with pre-existing CVD are far more likely to develop cardiac events in the setting of wildfire smoke exposures. Clinicians can reduce susceptibility by aggressive management of traditional risk factors, including hypertension, diabetes, and atherosclerotic disease.

In smoke-prone areas, medical therapy should be optimized annually before the start of fire season.

#### Cleaner Indoor Air at Home

Every exposed home should prioritize cleaner indoor air. As much as 65% of exposure to outdoor air particles occurs while indoors. Protecting a single room is often easier and less expensive than protecting an entire house or apartment. Individuals should choose a room(s) where they spend significant time (eg, bedroom) with few windows or doors. Keeping indoor air clean is best achieved by the following steps.

#### Seal the Building Envelope

The building envelope should be sealed to reduce the infiltration of outdoor air and to facilitate indoor air

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**Figure 3. Summary of approach to protecting cardiovascular health from wildfire smoke.**

Communities, health systems, and individuals in high-risk areas may take action indicated to prepare for wildfire season and reduce harmful smoke exposures. CVD indicates cardiovascular disease; HVAC, heating, ventilation, and air conditioning; PAC, portable air cleaner; PM$_{2.5}$, fine particulate matter; and PSA, public service announcement.

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<td>• Reduce smoke susceptibility with heart healthy lifestyle and cardioprotective medications</td>
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cleaning.\textsuperscript{75} Doors and windows should be kept closed.\textsuperscript{20} In addition, any indoor sources of air pollution should be discontinued (eg, smoking, incense, solid fuel–burning stoves and furnaces, dry sweeping or vacuuming).\textsuperscript{20}

**Central Air**

Some heating, ventilation, and air conditioning (HVAC) or mechanical ventilation systems can be fitted with high-efficiency filters, which remove the majority of PM\textsubscript{2.5} from incoming or recirculated indoor air.\textsuperscript{16,20,69,76} When using HVAC air filtration, it is important to use the most efficient in-duct particle filter that conforms to the specific systems in place (Minimum Efficiency Reporting Value 13 or higher is best).\textsuperscript{69} Filters should fit snugly and be replaced when soiled. Initial studies affirm that this may translate into a cardiovascular benefit: analyses of cardiovascular hospitalizations in the United States found that air conditioning significantly modifies the relationship between PM exposure and cardiovascular hospitalization.\textsuperscript{77}

**Portable Air Cleaners**

In homes without effective central air filtration, portable air cleaners (PACs) are one of the most protective technologies available for reducing wildfire smoke exposure.\textsuperscript{78} Carefully controlled studies have demonstrated that PACs with high-efficiency particulate air (HEPA) filters can remove the majority of indoor PM\textsubscript{2.5} with significant reductions in average individual exposures. For example, a recent study reported that PACs reduced PM\textsubscript{2.5} from wildfires by 73\% during working hours in an active office setting.\textsuperscript{79} Such reductions in exposure appear to translate into cardiovascular benefit. A recent meta-analysis of 10 randomized blinded controlled trials demonstrated that PAC use was associated with a lower systolic blood pressure by an average of 3.9 mm Hg (95\% CI, 7.0 to 0.9).\textsuperscript{80} A modeling study estimated that if PACs were adopted widely across the United States, the subsequent reduction in PM exposure from various sources would prevent approximately 64,000 premature deaths annually.\textsuperscript{74} Several considerations are needed for a PAC to be effective. The PAC must be used for the volume of space it is designed for, typically an average room sealed off from outdoor air.\textsuperscript{16,76} Additional information is available from the EPA\textsuperscript{68} and other groups\textsuperscript{81} (Table).

**Be Mindful of Competing Risks**

Individuals must be mindful of the competing risk of high temperatures (eg, heat stroke) that may occur with decreased ventilation or air conditioning.\textsuperscript{16,20} Maintenance of comfortable indoor temperatures should not be compromised for enhanced smoke reduction, because the immediate health risks for extreme heat are generally larger than those related to smoke. If an individual cannot create a cleaner room with appropriate temperature regulation, then they should seek daytime relief in community cleaner air shelters (see below).\textsuperscript{20} In addition, individuals remaining indoors should be mindful of the competing risk of transmission of infectious diseases, such as COVID-19.

**Cleaner Air Shelters**

Some residential buildings do not protect against penetrating smoke, particularly among disadvantaged communities and in low- and middle-income countries.\textsuperscript{17,20} The EPA recommends opening community cleaner air shelters.

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**Figure 4. Risk assessment: factors determining exposure and susceptibility.**

Highly exposed individuals are exposed to higher concentrations of wildfire smoke. Susceptible individuals are at elevated risk of cardiovascular complications for any given level of wildfire smoke exposure. Individuals at highest risk are both highly exposed and susceptible. Clinicians can screen for these factors to identify patients at elevated risk, for whom interventions to reduce exposures may be warranted.
facilities for these groups at PM$_{2.5}$ concentrations $>35.5$ µg/m$^3$. Health care systems can partner with local governmental and nongovernmental organizations to provide cleaner air shelters for such individuals. Shelters can provide a temporary respite from smoke, or potentially provide housing until severe smoke abates. Possible locations include hotels, hospitals, schools, libraries, malls, sports facilities, and senior centers.

**Cleaner Indoor Air in Health Facilities**

Hospitals, clinics, and long-term care facilities should strive to become clean air facilities. This often requires strategies different from those used in homes or other buildings.

**Optimize Central Air Filtration**

Health facilities have complex filtration and ventilation systems, and intake of outdoor air may be required for these systems to work. As a result, hospitals and clinics need individualized approaches. Managers should consult with HVAC specialists before wildfire season to test baseline indoor air quality and determine how best to limit smoke intake while maintaining positive indoor pressure and essential ventilation services. Guidance for hospitals and clinics to attain cleaner air during wildfires is provided by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers.

**Reduce Outdoor Air Infiltration**

The building envelope should be inspected for leaks. Points of entry and exit should be restricted as much as possible, prioritizing double doors with vestibules. Signage should be placed throughout the facility to remind individuals to keep windows and doors closed. Outdoor air dampers should seal tightly when closed. Filter edges must be tightly sealed around ventilation systems. In addition, indoor sources of air pollution should be reduced or directly ventilated, if possible (eg, laboratory equipment).

**Monitoring**

Health facilities should continuously monitor and compare outdoor and indoor PM concentrations to assess the effectiveness of cleaner air interventions. Changes in indoor pollutant concentrations can signal building managers to adjust HVAC systems and other interventions.

**Create Designated Cleaner Air Spaces**

Facilities unable to provide cleaner air throughout the building should create clearly designated and monitored cleaner air spaces. PACs can be used to improve air quality in these areas.

**Facemasks**

During wildfire events, susceptible individuals should consider wearing a personal respirator as a supplement to cleaner indoor air. Particle respirators can effectively reduce PM$_{2.5}$ exposures if they are well-fitted to the wearer. There are many types of particle respirators available (eg, N95, CAN95, KF94, etc), all offering similar protection despite being tested by different standards. Although a fitted particle respirator is preferred, a well-fitting 3-layer cloth or disposable surgical mask can...
also provide moderate protection. Simple 1-layer cloth masks, bandanas, scarves, T-shirts, or other face coverings provide essentially no protection.

Studies demonstrate that wearing a particle respirator in environments with elevated ambient PM2.5 levels may improve surrogate markers of cardiovascular risk. For example, a case-crossover trial in Beijing enrolled 98 patients with coronary artery disease who performed a scripted walk with and without an N95 respirator. Use of an N95 was associated with significant reductions in blood pressure, maximal ST-segment depression, and higher heart rate variability.

Minimize Outdoor Activities

Individuals should be instructed to reduce time outdoors during elevated wildfire smoke exposures. Wildfire pollution levels often follow a diurnal cycle based on local wind, weather, and topography. Individuals can monitor these trends and relegate essential outdoor activities or errands to lulls in exposure. Errands can also be reduced by stocking up on nonperishable food, sanitary supplies, prescription medications, and other essentials before wildfire season.

The long-term health benefits of routine exercise have been observed in large epidemiological studies to outweigh the risks of chronically high ambient pollution levels. However, the risk-benefit ratio of exercising during short-term wildfire smoke exposure specifically has not been studied. For healthy individuals choosing to exercise outdoors, the EPA recommends limiting outdoor physical activity at PM2.5 levels above 55.5 µg/m³, and ceasing outdoor physical activity at levels above 150.5 µg/m³ or during periods of heavy smoke. Healthy individuals should also avoid high-intensity or prolonged exercise during smoke events. Those with pre-existing CVD should avoid all outdoor exercise during polluted conditions.

As an alternative, individuals should pursue exercise in a clean air environment (eg, gym with central air filtration).

Automobile Modifications

Individuals can take precautions while driving to reduce their exposure to wildfire smoke. Closing windows and using cabin air filters lowers in-cabin PM2.5 levels and has been shown to reduce markers of oxidative stress. In addition, turning on air conditioning and “recirculate” mode has been associated with improved heart rate variability. High-risk individuals who spend significant time driving also may consider installing high-efficiency cabin filters, which are more effective than standard filters at reducing PM2.5 levels. Prolonged operation of air conditioning on recirculation mode can lead to buildup of high levels of exhaled carbon dioxide, which can be a safety concern; briefly opening windows every 15 minutes will minimize this potential.

Air Quality Monitoring, Forecasting, and Response Plans

Before the start of wildfire season, patients should be connected to services providing forecasts and alerts about hazardous smoke levels in their vicinity. Patients can use this information to guide response plans and behavior modifications (eg, when to stay indoors, use air filtration, wear a respirator). Individuals who follow behavioral recommendations from Air Quality Indexes can successfully lower their individual exposure, although it remains unclear whether these indices reduce cardiovascular outcomes.

Forecasting services are available to estimate smoke exposures for the coming days and months (Table). Local air quality indices (eg, EPA AirNow Wildfire Map) provide real-time estimates of local pollution levels. Local smoke advisories can provide alerts by phone or email. For example, the EnviroFlash and BlueSky websites provide daily air quality forecasts and alerts from local agencies. Smartphone applications (eg, SmokeSense, AirNow, AirRater) can provide users with real-time air quality estimates and customized alerts.

Clinicians should be aware of sensors purchased for individual use. Although individual monitoring devices hold the promise of providing personalized estimates not possible from modeled estimates, questions remain about accuracy, precision, cost, and reliability under different meteorological conditions. Various low-cost sensor networks may provide more reliable local exposure estimates.

Health care providers may wish to develop their own alert system for susceptible patients. Exposure maps could be integrated into electronic medical records to provide clinicians with exposure forecasts at the patients’ home addresses. Alerts can be sent by phone, email, social media, or medical record services (eg, MyChart), or posted on the provider’s website. The US Centers for Disease Control and Prevention provides additional guidance on how to use social media for health messaging.

Preparing Health Systems for Wildfire Season

With the threat of wildfires increasing globally, the number of affected health systems will continue to grow. Health systems can assess their risk using the forecasting tools discussed above (Table). Systems at risk should make preparations for wildfire season (Figure 3) to protect their susceptible patients and avoid shortfalls in beds, supplies, human resources, and key partnerships.

Wildfire Leadership Team

Health systems should designate an interdisciplinary team to make preparations for wildfire season. Key responsibilities of this team include educating the health workforce; drafting public messaging; ensuring clean indoor air for system facilities; determining a source for exposure estimates; developing partnerships with clean air agencies; securing supplies for at-risk populations (eg, respirators, PACs); and advocating for policies to protect the local community.

Educating Clinicians

Clinicians should receive some training on the risks of wildfire smoke exposure, as well as specific interventions...
and resources to recommend to patients. The EPA’s “Wildfire Smoke Guide for Public Health Officials” provides many useful resources. Clinicians can participate in a related online training course, “Particulate Pollution and Your Patients’ Health,” for which they can receive continuing education credits. Last, medical education and training should include the pathophysiology and air pollution-attributable diseases.

**Broader Policy Considerations**

As leaders in their communities, health care systems can provide a strong voice for political action. Building codes can be modified to require indoor air filtration, sealing of building envelopes, and cleaner air spaces. Resources are needed to finance firefighting efforts and prescribed burns of underbrush overgrowth that can prevent larger fires. Occupational standards are needed to protect outdoor workers (eg, agricultural workers), such as the standards adopted by California in 2019. In addition, regulations and penalties can reduce agricultural burning, tropical rainforest burning, and accidental ignitions along the wildland-urban interface. Investments in air pollution control typically bring economic benefits through decreased health care costs and the increased productivity of healthier populations. In the United States, for example, every dollar invested in air pollution control has yielded an estimated return of $30.

**Forecasting Tools**

Current long-term forecasting platforms predict wildfire potential on the basis of recent meteorological data (eg, National Interagency Fire Center Outlooks). However, these platforms do not provide long-term forecasts for smoke exposure specifically. Improved forecasting tools are needed to estimate smoke exposures for the coming season. Historical data on smoke exposures can be used to identify high-risk areas; although this approach requires prospective validation. These forecasts could be integrated with data on social vulnerability to identify areas at highest risk.

**Trials of Targeted Interventions**

Larger randomized trials are needed to evaluate the efficacy of interventions to reduce smoke exposures and health outcomes. Although some trials have evaluated the effect of interventions on surrogate markers of cardiovascular health, future trials are needed to assess the effect on cardiovascular outcomes.

Trials may investigate both individual- and community-level interventions. Key individual interventions to be tested include behavioral modifications; personal respirators (eg, N95s); portable air cleaners; central air filtration; and cardioprotective medications. A recent expert workshop concluded that indoor PACs with high-efficiency particulate air filtration were the most favorable technology to adopt for clinical trials for PM reductions. Key community interventions to be tested include alert/advisory messaging systems; cleaner air shelters; and enhanced firefighting and forest management practices.

Trials should assess how the efficacy of the intervention varies with different parameters, including baseline pollution levels; total reductions observed for different pollutants (PM, O, NO, etc); and efficacy in susceptible subgroups (eg, pre-existing CVD). Careful data should be collected about air pollution components and the fraction attributable to wildfire smoke versus fossil fuel emissions or other sources. Studies should involve minority communities and low- and middle-income countries, which are underrepresented in the existing literature and likely

**FUTURE DIRECTIONS**

More research is needed to delineate the relationships between wildfire smoke exposures, cardiovascular outcomes, and the efficacy of targeted interventions. Research endeavors will benefit from an interdisciplinary approach, combining expertise in clinical care, toxicology, physiology, epidemiology, exposure modeling, forestry, environmental studies, economics, social science, and public policy. Federal agencies can develop a comprehensive national research program combining varied expertise to evaluate and reduce the risks of wildfire smoke. Research centers can be located in affected regions and house mobile teams to implement research action plans on unpredictable fire events. Key research questions include the exposure-response relationship and trials of targeted interventions. More research dollars are needed to support these efforts.

**Exposure-Response Relationship**

More data are needed on the effects of long-term or repeated exposures to wildfire smoke, and whether such exposures cause or accelerate atherosclerotic CVD. Studies are needed to determine whether periods of clean air between wildfire smoke exposures may facilitate physiologic recovery. The exposure-response relationship also must be defined for susceptible groups (eg, those with pre-existing CVD or genetic predispositions), for highly exposed groups (eg, outdoor workers), for different life stages (eg, pregnant women and the elderly), and for different sources and components of wildfire smoke. Toxicology research and observational studies can determine how the composition, toxicity, and health effects of wildfire smoke differ from other sources of PM. Studies are needed to determine “how clean is clean enough,” that is, what level of reduction is necessary to achieve a cardiovascular benefit at the individual and population level. This information is critical to guide decisions on exactly when, how, and for whom to intervene. Last, studies are needed to understand potential extracardiac effects of wildfire smoke, including neuroinflammation and neurodegenerative diseases, pulmonary diseases, preterm birth, and malignancy.

**STATE OF THE ART**

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to suffer the greatest growth in wildfires this century.\textsuperscript{11} To ensure scalability of interventions, studies should also collect data on cost-effectiveness and assess effects on other social and structural determinants of health. The fact that wildfires often are unpredictable and short-lived is a key limitation to implementing prospective randomized trials. It may be difficult to secure ethical review board approval and enroll a sufficient number of participants for an appropriately powered prospective trial.\textsuperscript{11} Difficulties with enrollment leading to low case counts and wide CIs likely contribute to the presence of null associations in the literature.\textsuperscript{2,11,12} Other causes of null studies likely include no accounting for cumulative smoke exposures; exposure misclassification because of dependence on air quality monitoring stations or satellite imagery; and actual differences in toxicity of smoke from different fires.\textsuperscript{11} To overcome these challenges, investigators may target more highly exposed and susceptible groups, intervening in regions with the highest exposure levels and high-risk patient populations. In addition, packages combining multiple interventions may provide a stronger effect size, and the use of composite end points may increase event rates. Initial studies may need to start with a surrogate end point such as blood pressure reductions, which is well-validated as an end point because it leads to proportionate reductions in cardiovascular events.\textsuperscript{76}

\section*{CONCLUSIONS}

Wildfires have become increasingly common and severe and will continue to worsen for the foreseeable future, posing a grave threat to global cardiovascular health. Wildfire smoke exposures are quantifiable and modifiable at the individual level. Clinicians and provider organizations therefore have an opportunity and a responsibility to help mitigate these exposures in their service populations. We provide a set of evidence-based interventions for patients and communities to protect cardiovascular health.

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